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THESIS

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by

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ABSTRACT

A multichannel frequency division multiplexed FM telephone system is presented. The system is intended for use in organizations where large numbers of telephones are normally installed and is compatible with conventional switchboards. Advantages provided by the system are: reductions in installed wiring, the ability to relocate telephone sets by the subscriber, and compatibility with other coaxial cable systems.

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I. INTRODUCTION

Organizations such as hospitals, hotels, and governmental offices require large numbers of internal telephone extensions. Existing systems require installed wire pairs dedicated to each extension. Initial installation costs are high and changes in extension locations must be made by telephone company technicians. In addition, users such as hospitals and hotels normally have coaxial cables for television installed which have a surplus of bandwidth when used only for entertainment television.

The system proposed would allow the installation of a multiplex telephone network that is compatible with cable TV. Considerable savings can be realized in the short term by the reduction of wiring costs in new construction and in the long term by the capability to add additional extensions without adding additional cables. Over the life of the system more savings would occur because of the portability of the telephone sets. Relocation of an individual subscriber's telephone set would require only the connection of a coaxial plug. The subscriber would retain his number and hence not require switchboard or directory changes. In addition, a relocation would be made by the user without telephone company assistance.

Developments in multiplex telephone and cable TV are included in the following pages. Recent developments in cable systems were particularly important in the design and feasibility considerations for this system.

Solid state and integrated circuit technologies were utilized in designing the system. Existing integrated circuits were used when they permitted more economical circuits than were possible with discrete components. Unfortunately several initially promising components such as phase locked loops could not be used because of bandwidth limitations.

II. MULTIPLEX TELEPHONY IN THE UNITED STATES

The history of multiplex telephony is in effect the development of this communications method by the American Telephone and Telegraph Company. The Bell System, as it is more commonly referred to, dominates the national industry and has a great influence in international telephony progress and policy. An outline of the development of multiplex telephony by the Bell System is therefore typical of international progress and is virtually a complete chronicle of American progress.

The principle of multiplexed, wire carried communications predates, and was instrumental in, the development of the telephone. Alexander Graham Bell's initial research

was directed toward the perfection of a "harmonic telegraph". His concept was that of mechanically producing audio frequency vibrations and then transmitting several of these frequencies over a common transmission line. (Ref. 1) A more efficient telegraph network could then be had. At the receiving station another mechanical device, usually a tuned metal reed, would vibrate when the appropriate harmonic was received. Quite by accident during his harmonic telegraph research Bell and his assistant, Thomas A. Watson, discovered that not only could invariant frequencies be transmitted and detected, but also the modulations of the human voice. Bell soon abandoned his primitive frequency multiplexing research for work on the equally primitive voice communications system. As a result of his work he received his historic patent, number 174,465, in 1896 for "An Improvement in Telegraphy," i.e. the telephone.

The combination of frequency multiplexing from the harmonic telegraph and voice modulation from the telephone had to wait until the telephone was further perfected and the demand for circuits was high enough to justify the complexities of multiplex telephony.

The telephone was limited to local intracity use when first developed due to the lack of a suitable wire for intercity connections. (Ref.2) With the application of hard drawn copper wire to open wire construction by Thomas B.

Doolittle "long distance" connections became possible. In 1884 a line was strung between Boston and New York. Further progress in an intercity telephone network awaited the invention of the electronic vacuum tube by Lee DeForest. Dr. H. D. Arnold proposed in 1915 that the vacuum tube be used to create practically perfect telephone transmission over long distances.

In 1892 John Stone in the United States and Pupin, Hutin, and LeBlanc in Europe devised schemes for telephone multiplexing. Spark gap generators were used to produce the carrier frequency. Signal amplification was at that time impossible. Experiments by Major G. O. Squier, head of the United States Army Corps at Fort Monmouth, New Jersey, with multiplex transmission over a short cable in 1910 further laid the foundation for future practical systems. (Ref.3) It might be noted that the term multiplex implies frequency multiplex, versus time multiplex. Until the development of solid state electronics the promise of time division multiplex was out of practical reach for telephony. Time division multiplexed telegraphy could be accomplished through the use of mechanical commutators however.

In 1918 the Bell System installed a carrier current telephone circuit using open wire construction between Pittsburg and Baltimore.(Ref.4) It provided four talking channels for each wire pair and was designated the A system. This

was to be the first of a long series of alphabetically designated intercity systems. In this system a connection was duplexed with both directions of transmission on the same frequency. Hybrid coils were used to separate the send and receive signals. The hybrid coil system gradually fell into disfavor because of maintenance difficulties. By 1923 the Bell System boasted of a carrier system "That if laid end to end would stretch half way around the globe." To be exact they had a 29 channel capability over 3,941 miles or a total of 14,676 channel miles. The longest link was from Harrisburg to Chicago, a distance of 742 miles.

In 1920 the three channel Type B system was introduced. It used separate frequencies for send and receive and thereby did away with the troublesome hybrid coils. As with the type A system amplitude modulation was utilized. By 1923 the advantages of multiple wire cables over open wire lines had been recognized and installation of aerial cables was under way. In addition to telephone circuits these systems also carried telegraph circuits. A typical network installed between Denver and Los Angeles in 1924 had three telephone and 14 telegraph circuits operating on four wires. In the type A system single sideband (SSB), supressed carrier was used, but the type B system was SSB, with carrier.

Paralleling the development of the multiplexing systems were improvements in the transmission medium. The advantages

of cable use were recognized, but the state of the art in cable construction did not yet give cables an unqualified advantage over the older open wire scheme. Cable transmission became the dominant mode when circuit requirements became too large for practical open wire construction and when telephone repeaters were perfected that could compensate for the cables' large losses. The Bell System then gradually changed from an exclusively open wire network to a mixed medium network when first multiwire cables, then coaxial cables, and finally microwave links were added.

The first long distance toll cable in the United States was placed in service between New York and Philadelphia in 1906. The cable installed between Chicago and New York in 1918 was typical of those in use and contained 300 circuits in a 2 5/8" diameter lead sheathing. (Ref. 5)

Further research led to the introduction of the type C system in 1925. It was a three channel system that used single sideband, suppressed carrier transmission. In this improved system equal spacing of channel frequencies had been abandoned in favor of variable spacing. This technique increased the efficiency of bandwidth usage. As with the type B system different frequencies were used for transmitting the send and receive components of each circuit. Frequencies no higher than 30 KHz were used because of

open wire construction predominance in the existing Bell System network and the limited bandwidth it permitted.(Ref.6)

The next system developed was the type D which provided a single channel carrier circuit for short haul use. It again was a single sideband, suppressed carrier, amplitude modulated scheme.(Ref.7)

Multiple channel systems previously discussed were all for toll (long haul) circuits. By 1933 the Bell System could see the need for multiplex systems that could increase the capacity of shorter trunks. However the depression allowed only research on and not installation of such systems.(Ref.8)

The need for broadband communications capabilities also began to be apparent in the 1930's. An electronic curiosity, the television, was one system that would require broader bandwidths than were currently available. Therefore coaxial cables, whose characteristics were predicted by electromagnetic theory, came under scrutiny. In 1934 the Bell System was constructing and testing various types of coaxial cable with an eye toward improving toll circuit capabilities as well as opening up a new communications medium.(Ref.9) The first coaxial cable system was installed between New York and Philadelphia in 1935. It was 95 miles long, had repeaters every 10 miles, and had a bandwidth of 1 MHz. It could carry 240 simultaneous two way conversations.

These channels were collected in 12 channel "groups." Conversion to subcarrier frequencies was done in two stages of modulation.

The type K system, introduced in 1937, used the group modulation principle with transmission over a multiple wire cable.(Ref.10) Other important features of the system were repeaters at 17 mile intervals and 4 KHz channel spacing. It was predicted at the time that the end of open wire toll construction was in sight and that the economies of the new system would make short haul multiplexing a strong possibility.

In 1938 the first long distance transmission of television over a coaxial cable had been carried out on the Philadelphia to New York, 1 MHz cable.(Ref.11) The results were not satisfactory for commercial use, but they pointed the way toward wider bandwidth coaxial cable and the simultaneous multiplexing of television and telephone on the same cable. Three additional carrier systems were introduced in the late 1930's. The type H system was developed as an improvement on the existing type D system.(Ref.12) One of its features was the capability to include repeaters for improved performance. The 12 channel type J system included many features of the type K, but was intended for open wire installations. As such it was used to supplement the existing type C system. The type M system used high voltage lines

as its transmission medium and found only limited use. Practical toll coaxial cable transmission was introduced by the type L1 system.(Ref.13) It had the capability of carrying 480 long haul channels. In addition 120 short haul channels could be utilized if necessary. The cable's bandwidth was 2 MHz.

With the type N1 system the Bell System improved multiwire cable capacities in 1950.(Ref.14) It was designed to carry as many as 1800 channels on a 300 pair cable from 15 to 20 miles. Increased distances could be achieved if necessary. A new technique used was compression and expansion of speech volume which permitted reductions in crosstalk and noise. Out of band signaling was added to give an associated signal channel just above each voice channel. As with other large capacity systems the 12 channel grouping scheme was used.

As a result of extensive research in microwave devices the Bell System was able to open the TD2 microwave multiplex system in 1950. Frequency modulation was used in the TD2 to provide 6000 low noise channels. A prime reason for the microwave system's installation was the desire to establish a nationwide television transmission network. The system supplemented the existing telephone cables which were unable to meet an unprecedented postwar demand for circuits. Creating the microwave network was a major undertaking by

any standard. Not only did new types of terminal equipment have to be developed, but a nationwide net of transmission stations and repeaters with their associated equipments had to be both designed and manufactured. The requirement for even more circuits in later years resulted in the later development of the TD3, TH, TJ, TL, and TH3 systems.

As a further step to improve the utilization of existing open wire installations, the type O system was put in commercial service in 1952. It was intended for circuits ranging from 15 to 150 miles long and was the open wire counterpart of the type N cable system.(Ref.16) This new system used the signaling and noise reduction schemes introduced in the type N, but used single sideband instead of the N's simpler double sideband method. Full capacity of the type O was 16 channels, arranged in groups of four.

The L3 coaxial system was placed in operation in 1953. It had a capacity of 1860 telephone channels or in a second version 600 channels. The L3 was designed as an improvement on the L1 and as such had as a prime design consideration the reuse of L1 facilities, equipment, and cables.(Ref.17) The L3's parameters were based on long haul usage of 4000 miles.

Solid state devices came into use in the type P1. Designed in 1956 for rural use it provided up to four stackable channels for either open wire or cable installations. As

with other wire carrier systems amplitude modulation was used for simplicity.(Ref.18) Rural usage was also envisioned for the type T1 system in 1962.(Ref.19) Because of further improvements in solid state devices and coding procedures it was able to utilize time division multiplexing in conjunction with pulse code modulation (PCM) and had a capacity of 24 channels. In a move to standardize interfaces the Bell System catagorized their multiplex terminals as "L Systems."(Ref.20) The L multiplex terminals were then subdivided into systems of different capacities and capabilities. These terminals were designed to operate with the L1, L3, and L4 coaxial cable lines and with the TD2, TD3, TH, TJ, and TL microwave links. Single sideband with 4KHz channel widths was used. Continued improvement of older systems resulted in the combination of the type O terminals with the N1 carrier lines to produce the ON1.(Ref.21) Further improvements upped the ON1's 16 channel capacity to 24 channels in the ON2. A solid state, 12 channel, double sideband, amplitude modulation scheme was used in the advanced N2 system. Again the upgrading process came into play and the N3 with 24 channels was produced, but with single sideband vice double.

The latest systems in use with the Bell System are the TH3 microwave system (Ref.22), the L4 coaxial cable system (Ref.23), and the T1 time multiplex system. The first two

are for use between switching centers, while the third is used to increase capabilities in rural and other low density areas. None of these systems are suitable for use within a large suscriber's organization, such as a hotel or office building. Nor are plans to introduce systems for such use in the near future apparent. Research is being carried out in new methods of transmission such as laser beams and millimeter waveguides. The future will probably mirror the past. There will be periodic changes in transmission media as technology permits, followed by continued updating of equipment. Each new system will share some of the equipment of older systems and the basic channel parameters will remain unchanged. A trend toward systems with shorter economical ranges seems inevitable because of the continued increase in demand for telephone circuits and broadband data links.

III. DESIGN CONSIDERATIONS AND SPECIFICATIONS

A. DESIGN CONSIDERATIONS

In order to achieve economies over existing telephone systems the proposed system must meet two basic requirements: it must be compatible with standard PBX switchboards and it must be capable of sharing coaxial cables with cable TV systems. The compatibility with existing telephone equipment and transmission parameters allows installation of this system with a minimum of interface problems. There is no requirement for additional equipment to match this system to standard telephone company equipment. A bonus derived from this compatibility is the practicality of installing this system in existing installations in order to boost the capacity of installed wiring. Older buildings, for instance, might be made suitable for occupancy by tenants who require more telephone extensions than any existing wiring could normally carry. If the installation of additional wiring was not economically feasible this multiplex system would fill an obvious need.

The installation of cable TV systems in buildings is becoming more common every day and is universal in newly constructed hotels, motels, and hospitals. New cable TV systems are required by law to be suitable for the future

incorporation of a two-way communications capability. Since the resultant installation of coaxial cables is becoming so prevalent, any additional capability that can be given them that reduces other wiring requirements results in an immediate savings. Studies have shown that to avoid the possibility of mutual interference additional communications signals should be well below the lowest standard TV broadcast band (Channel 2 at 54 MHz). An upper limit of 30 MHz on additional signals is generally considered sufficient(Ref.24).

In addition to the limiting design considerations above, other features were deemed worthy of inclusion. In anticipation of future nationwide use of tone generation dialing, the system was designed to use this method signaling. With modifications the older make and break dialing method could be used. A parts' cost of $35 per extension was set as a goal. The cost of the system manufactured in quantity would be about three times that figure. The individual telephone set, which would contain a conventional handset and dial tone generator, in addition to the multiplexing circuitry, would have to be easily portable in its final manufactured form. The power for each extension would come from a central supply. The extension would therefore not have to be located near a conventional AC outlet.

To free the system from high ringing voltages, ringing is accomplished with an amplified audio tone. Individual

extensions could be given unique ring tones. Such a feature is convenient in crowded offices which contain several extensions. Send and receive bands would be frequency separated to reduce crosstalk and to avoid the complexity of directional signal separation circuits. FM was chosen over AM in order to take advantage of the noise rejection features of the former. Standard 10.7 MHz IF was used, allowing use of available integrated circuits and filters.

To as great a degree as possible circuits such as oscillators were designed to be suitable for use in several components of the system. This minimizes the number of unique circuits in the system and increases standardization. Each transmitter/receiver unit is suitable for use over the entire 5-30 MHz system frequency range with a minimum of changes. Shifting a unit from one band to another requires only substitutions or tuning of tuned circuits. In the system's final manufactured form that might be accomplished by small plugin modules.

B. FREQUENCY ALLOCATION

The cornerstone of any frequency division multiplex system is the frequency allocation plan. Design considerations and tradeoffs hinge on the available frequency spectrum and the number of channels desired. As previously mentioned this system is limited to a band of about 25 MHz

between 5 MHz and 30 MHz. Since the system is intended for use with conventional telephone networks, the standard 4 KHz audio channel was adopted. Figure 1 illustrates the audio channel, the voice bandpass within that channel, and the 20 Hz out-of-band ring frequency. It might be noted that additional out-of-band signaling is possible in the upper section of the channel between the voice bandpass and the channel boundry. Figure 2 contains a diagram of a pushbutton dialing keyboard that would be suitable for use with the proposed system. In this case the dial signal is in-band and each digit or character has a pair of corresponding frequencies, one from the low-band and one from the high-band. Although only 12 buttons are presently used in commercial installations, 16 buttons are possible if the spare frequency combinations are used.

Because a key component of the proposed system is an integrated circuit originally intended for use in FM broadcast receivers, the standard maximum frequency deviation of ± 75 KHz about the carrier is used. As a precaution against adjacent channel interference ± 100 KHz is allowed for each sideband. The proposed system therefore requires 200 KHz for each one-way channel and hence 400 KHz for each extension, as shown in Figure 1.

Of the original 25 MHz available a portion around the 10.7 MHz intermediate frequency (IF) of the receiver circuit

is unusable. The remaining spectrum has been broken up into 60 channels in Table 1. Channels 1 thru 12 are below the IF gap and 13 thru 60 above. The lower 12 channels are less desirable for use than the 48 upper channels. Because all carriers are on odd hundreds of kilohertz, second harmonic interference is avoided. However third harmonic interference between the upper and lower channels is possible. Therefore if an installation required 48 or fewer extensions, the lower group would be left vacant. If an installation called for more than 60 extensions two or more coaxial cable trunks would be necessary. For instance if a building required from 30 to 60 extensions per floor a trunk could be run to each floor. The desired flexibility in extension relocation would be somewhat limited in such an installation. An extension could not be relocated from a plug supplied by one trunk to a plug supplied by another trunk without a cross-patch being made at the PBX switchboard.

In installations which do not require the simultaneous transmission of both telephone circuits and broadcast television, the systems spectrum could be extended above 30 MHz, making additional channels available. Limiting factors on the number of channels that might be added could be the capability of the coaxial cables to carry the total DC power requirements for the extension multiplex units and the possible occurrence of harmonic interference problems.

C. SYSTEM SPECIFICATIONS

Method of modulation:	Frequency modulation, double sideband, with carrier
Maximum carrier deviation:	$\pm$ 75 KHz
Bandwidth per oneway channel:	200 KHz
Total bandwidth per channel:	400 KHz
Audio bandwidth:	4 KHz
Carrier frequency range:	5-30 MHz
Receiver IF frequency:	10.7 MHz
Maximum number of extensions:	60
Signal to noise ratio:	-45 db
Harmonic distortion:	-40 db
Power supply voltage:	10-12 VDC
Power usage per extension:	1 W
Impedance at PBX terminals:	600 Ohms
Ring signal:	In-band audio tone
Dial signal:	In-band audio dual-tone
Crosstalk between adjacent channels:	-60 db

IV. THEORY OF OPERATION

A. GENERAL ASPECTS OF SYSTEM OPERATION

The multiplex system's configuration is illustrated in Figure 3. Each extension multiplex unit (EMU) is an FM transceiver. The PBX multiplex unit (PMU) contains transceivers that closely resemble the extension units, but with additional features. Figure 4 breaks these units down into functional blocks. The system has two general operating modes that correspond to the two operating modes of conventional telephones. These are the hook-on and hook-off states and they refer to the status of the extension's handset. If the handset is in its cradle the extension is in the hook-on state and conversely if the handset has been removed from its cradle to send or receive a call the hook-off state exists.

The most common state for an extension is the hook-on. In this case the extension is idle and is ready to receive a call. The PMU's individual transmitter and receiver sets are energized. The transmitters are sending out unmodulated carrier signals to which the corresponding EMU receivers are tuned. The ring detector is also energized. The PMU audio signal switch is open, preventing 20 Hz ring signals from the PBX from reaching the PMU transmitter. At the EMU

the receiver is active, but not the transmitter which is turned off to conserve power and to reduce the number of active frequency bands.

If a call is received by the PBX for an extension the PBX selects the proper connection for the corresponding PMU set. The PBX would detect that a hook-on state existed using a DC resistance detector and would commence standard 20Hz rings. The ring detector would detect the rings and activate the ring tone generator. These ring tones would modulate the PMU transmitter. At the EMU the carrier would be demodulated and the audio ring tones amplified. The subscriber would then hear the extension's unique ring tone coming from the small ring tone speaker just as he would hear the bell in a conventional extension. When the call is answered by picking up the handset the extension's state would be changed to hook-off. The ring tone speaker would be disconnected and the handset connected to the EMU's circuits. In addition the EMU transmitter would be energized. The EMU transmitter's carrier would go over the coaxial cable to the PMU. The PMU receiver would sense the presence of the carrier and activate the audio signal switch which would in turn connect the PMU receiver to the PBX. The ring detector would be left on because only 20Hz ring signals are of sufficient magnitude to be detected by the ring detector so there is no possibility of speech signals keying the ring tone generator.

The PMU would now present the standard 600 ohm hook-off resistance to the PBX. The system would now be ready to carry a two way conversation over the activated extension.

If the system is in the hook-on state and a subscriber desires to make a call an abreviation of the previous sequence takes place. When the handset is removed from its cradle the ring tone speaker is disconnected and the handset, transmitter, and audio signal tone generator are placed in operation. The subscriber can then dial the desired number by keying the audio signal tone generator. The signal tones are within the bandpass of the telephone and are transmitted in the same manner as speech. Switching processes are carried out at the telephone company's switchboard. Busy and out of order signals from the PBX would also be handled in the same manner as speech. At the PMU the extension's carrier would be detected and the audio signal switch would be activated as before.

When the system is in a hook-off state the system is in the operating setup as described in the above paragraph. Both sets of receivers and transmitters are energized and the PMU presents the proper 600 ohm resistance to the PBX. The ring detector is activated but is not subject to signals that would cause it to key the ring tone generator.

B. PBX MULTIPLEX UNIT CIRCUIT OPERATION

1. Transmitter Operation

Figure 5 presents the schematic diagram of the PMU transmitter and Figure 6 tabulates the values of the components.

The transmitter is linked to the PBX at the terminals labeled "FROM PBX." When the extension is in the hook-on mode, i.e., the extension is not in use, relay/switch X1 is open. A ring signal would be transmitted to the ring detector circuit by the transformer T2. The full-wave rectifier consisting of diodes: D5, D6, D7, and D8, dropping resistor R11 and smoothing capacitor C10, would convert the 20Hz ring signal to the 10VDC supply voltage for the ring tone generator. Since ring signals from the PBX are in the order of 90V, ordinary audio conversation signals which are in the order of 2V are too small to activate the ring tone generator.

The ring tone generator is a phase-shift oscillator which generates an audio tone. C14 provides the feedback necessary for oscillation and a portion of the required phase-shift. C11 and C12 complete the required phase-shift. By varying the values of C11 and C12 the frequency of the oscillator can be changed. In this manner each extension can be given a unique ring tone. Q5 is included as an

emitter-follower to prevent the loading down of the oscillator. C15 couples the ring tone generator to the transmitter and blocks DC.

If the extension is in the hook-up mode the EMU transmitter is activated and sends a carrier signal to the PMU receiver. The presence of this carrier is indicated by an increase of the voltage at the "METER" terminal of the PMU receiver and the corresponding terminal of the PMU transmitter. For typical operating conditions the voltage would go from 1VDC to 2+VDC. D2 and D3 bias Q1 so that a voltage of about 1.8VDC will turn Q1 on, this would in turn activate and close X1. D1 and C1 allow the circulation of currents through X1 and prevent voltage spikes that could damage Q1 or cause X1 to chatter. R1 serves tc seize the switchboard for outgoing calls by presenting the proper DC resistance of 600 ohms to the PBX busy detector. C2 prevents DC from reaching T1 which couples the balanced PBX terminals to the unbalanced circuits of the PMU. R2 may be varied to diminish the audio level from the PBX to prevent over deviation of the carrier.

The transmitter uses a varactor diode, D4, to FM the basic RF carrier generated by Q2 and Q3. C6 and L1 set the basic carrier frequency. For channelization of a production system these tuning components might be included in a plug-in module that would be factory tuned for an indicated

channel. C4 links the varactor with the tuned circuit so AF signals across D4 vary the total capacitive reactance of the tuned circuit and hence the frequency of the carrier. This basic circuit is used in both the EMU and PMU transmitters. In addition a modification of the circuit is used in the EMU and PMU receivers in their local oscillators. This dual use of the circuit would result in more economical production of the proposed system. R10 serves to increase the output impedance of the circuit. High output impedances for each transmitter are necessary because all channels are connected in parallel at the junction boxes. Low individual output impedances would result in mismatching the coaxial lines.

In an installed system the DC power supply would also be connected across the RF terminals at the junction box. DC voltage from this source would be carried to the EMU's on the same coaxial cable as the RF signals. Design of a suitable power supply was not included in the system as presented. In practice a 12VDC supply would be used. The voltage at each unit would then be within the design limits of the system, and in addition some leeway would be present to compensate for any loading down of the power supply if it did not act as a perfect voltage source. A 12 volt supply would also allow a convenient interface with an emergency battery power supply.

2. Receiver Operation

Figure 7 presents the schematic diagram of the PMU receiver and Figure 8 tabulates the values of the components. Figure 9 is a block diagram of the CA-3089 and Figure 10 is its schematic from Ref. 25. Figures 11, 12, 13, 14, 15, and 16 contain performance charts on the IC from the same source. Reference 26 also contains information on the application of the CA-3089.

The FM signal from the EMU is received at the terminals labeled "RF" and is amplified by Q4. R18 and R19 set the bias for Q4 and C14 blocks the DC carried by the coaxial cable. L3 and C12 form a tuned circuit that allows selective amplification of the individual channel's carrier. Q3 and Q2 and their associated components act as the receiver's mixer. Taking the amplified RF at the base of Q3 and the local oscillator signal at the base of Q2, the mixer produces the sum and difference frequencies. In the proposed system the local oscillator (LO) operates at a higher frequency than the channel carrier's and the difference frequency of 10.7 MHz is taken off the collector of Q3 as the IF. R13 and R14 bias Q2 and R12 and R15 bias Q3 to produce the desired non-linear operation of the mixer.

Q6, Q7, and their associated components constitute the LO. The basic oscillator circuit is the same as used in the multiplex unit transmitters. In this case instead of

modulating the output of the oscillator to carry audio signals, the output frequency can be varied to compensate for drift in the received carrier. The line labeled "AFC" from the CA-3089 acts as a current source to drive the LO's AFC circuit. Figure 15 is a graph of IF drift versus current output at pin 7 of the IC. R20, R21, R22, R23, R24, R25, and R26 form a biasing circuit that provides uniform AFC loop gain over the tuning range, prevents the IC's AFC circuits from saturating, and prevents the over-deviation of the LO output. Instead of using a varactor diode as was done in the transmitter circuit, a back-biased transistor, Q5, is used in the LO. As with the varactor the back-biased transistor's capacitance is also varied by the voltage appearing across it. This action is not as linear as it would be with a varactor, however since the circuit is only used to compensate for drift and not to transform an information signal the decreased linearity is tolerable and the use of a transistor represents a considerable savings over the use of a relatively expensive varactor. The output of the LO is coupled through C20 to the mixer at Q2.

The FM-4 is a crystal bandpass filter designed especially for FM broadcast receivers. It has a narrow bandpass about the standard FM receiver IF of 10.7 MHz, therefore it filters out all but the difference frequency from the mixer.

Pins 1 and 2 of the IC drive the first of three IF limiters in the chip. Pin 3 provides DC feedback. The limiters in turn supply three level detectors whose outputs are summed at pin 13. In a FM broadcast receiver this output would drive an S meter. For the proposed system however, this output provides a convenient method for sensing the presence of a received carrier and is used to drive the relay circuit in the PMU transmitter. The first level detector in the IC also provides AGC voltage at pin 15. In the proposed system the AGC feature is only used for tuning and trouble shooting purposes. The output of pin 8 comes from a quad limiter. L2 acts as a RF choke to block harmonics of the IF. L1, C2, and R1 are tuned to 10.7 MHz and drive the IC's detector. Pin 10 is fixed at a reference bias voltage and would be used as a return point for the AFC if that feature were not used. R6 and R5 set the squelch threshold of the IC. The squelch circuit reduces the side responses that are characteristic of limiter-discriminator receivers, as shown in Figure 16. In the proposed system the squelch control can also be used as a convenient method of decreasing the audio output of the IC without having to change fixed value components. The audio output of the IC is taken at pin 6. The internal output impedance is 5 KOhms, so the total impedance after R7 would be 7.5 KOhms.

Q1 and its associated components form an audio amplifier to bing the audio output of the PMU up to a suitable level for connection to the PBX at the terminal labeled "AUDIO TO PBX." Placing T1 at the collector leg of Q1 produces the desired balanced output with a minimum of components. A modification of this amplifier is also used in the EMU receiver.

C. EXTENSION MULTIPLEX UNIT CIRCUIT OPERATION

1. Transmitter Operation

Figure 17 presents the schematic diagram of the EMU transmitter and Figure 18 tabulates the values of the components.

The EMU transmitter is connected to a coaxial cable outlet at the terminal labeled "RF+DC." As the label indicates both carrier RF and DC supply voltages are carried by the cable. RFC blocks the RF from the DC supply lines while C8 blocks the RF out of the terminal labeled "RF TO RECEIVER," hence RF/DC separation for the entire EMU is accomplished in the transmitter section. The DC supply for the receiver is picked off after RFC and is routed via the terminal labeled "DC TO RECEIVER." S1 is activated by the handset hook. In the hook-on condition the switch is open and the transmitter is off, however DC still flows to the receiver which is active at all times in order to receive ring tone signals.

The handset and dial tone keyboard are the conventional types currently in commercial telephone sets. The frequencies generated by the keyboard are shown in Figure 2. If the proposed system were placed in production these items would be purchased directly from a telephone equipment supplier.

The transmitter circuit itself is identical to the PMU transmitter circuit. The output is again taken through R1, which increases the output impedance, back to the common coaxial cable connection.

2. Receiver Operation

Figure 19 presents the schematic diagram of the EMU receiver and Figure 20 tabulates the values of the components.

The EMU receiver obtains its RF and DC from the transmitter section as previously indicated. With the exception of the meter and audio amplifier circuits the two receivers are identical. In the PMU the meter current was used to control a relay circuit. In the EMU there is no corresponding relay so the meter output is used for tuning purposes only.

The audio amplifier of the EMU supplies both the handset and the ring tone speaker. S1 is controlled by the handset hook and is ganged with S1 of the EMU transmitter. When the hook-on condition exists S1 routes the audio to the speaker so ring tones may be heard. When the user picks up

the handset the switch disconnects the speaker and connects the handset so a call can be completed.

V. RESULTS AND CONCLUSIONS

The proposed system meets the basic requirements for a FM, frequency division multiplexed telephone system compatible with both existing telephone networks and broadcast TV cable installations. The frequency allocation plan presented indicates that there are a reasonable number of extension channels available within the suggested system bandwidth. Interference between individual telephone channels and between the telephone signals and TV signals should be minimal because of the conservative carrier frequency separation used and the wide gap between the lowest TV channel and the highest telephone carrier. Before the proposed system could be placed in commercial use extensive testing would have to be carried out to verify the lack of interference. This testing would include the simultaneous operation of several telephone and broadcast TV channels. In addition to determining mutual interference, interference from RF sources outside the system would have to be determined and minimized.

The performance of the system is tabulated in Section III C, SPECIFICATIONS. Manufacturer's data on the CA-3089 can be found in APPENDIX B, ILLUSTRATIONS. Comparison of

these data show that the system has a reasonable signal to noise ratio of -45db, but that the IC has a ratio in excess of -70db for strong received signals, indicating that the system has not realized optimum operation. The harmonic distortion realized of -40db was found to be highly dependent on the tuning of the various tuned circuits throughout the system. If the system were placed in commercial production using plugin modules containing the tuned components, these components would have to be tuned for minimum signal distortion as well as for optimum signal strength.

Reference 27 contains the CCITT (International Telegraph and Telephone Consultative Committee) standards for crosstalk in the telephone systems. The proposed systems crosstalk figure of -60 db is rated "Good" by these standards.

In summary the proposed system has achieved performance figures that indicate it is a feasible design for accomplishing the multiplex telephone concept.

APPENDIX A

CHANNEL FREQUENCY ASSIGNMENT

CHANNEL	LOWER CARRIER	UPPER CARRIER	CHANNEL	LOWER CARRIER	UPPER CARRIER
1	5.5	5.7	31	18.7	18.9
2	5.9	6.1	32	19.1	19.3
3	6.3	6.5	33	19.5	19.7
4	6.7	6.9	34	19.9	20.1
5	7.1	7.3	35	20.3	20.5
6	7.5	7.7	36	20.7	20.9
7	7.9	8.1	37	21.1	21.3
8	8.3	8.5	38	21.5	21.7
9	8.7	8.9	39	21.9	22.1
10	9.1	9.3	40	22.3	22.5
11	9.5	9.7	41	22.7	22.9
12	9.9	10.1	42	23.1	23.3
13	11.5	11.7	43	23.5	23.7
14	11.9	12.1	44	23.9	24.1
15	12.3	12.5	45	24.3	24.5
16	12.7	12.9	46	24.7	24.9
17	13.1	13.3	47	25.1	25.3
18	13.5	13.7	48	25.5	25.7
19	13.9	14.1	49	25.9	26.1
20	14.3	14.5	50	26.3	26.5
21	14.7	14.9	51	26.7	26.9
22	15.1	15.3	52	27.1	27.3
23	15.5	15.7	53	27.5	27.7
24	15.9	16.1	54	27.9	28.1
25	16.3	16.5	55	28.3	28.5
26	16.7	16.9	56	28.7	28.9
27	17.1	17.3	57	29.1	29.3
28	17.5	17.7	58	29.5	29.7
29	17.9	18.1	59	29.9	30.1
30	18.3	18.5	60	30.3	30.5

Table I. Channel Frequency Assignment

APPENDIX B

ILLUSTRATIONS

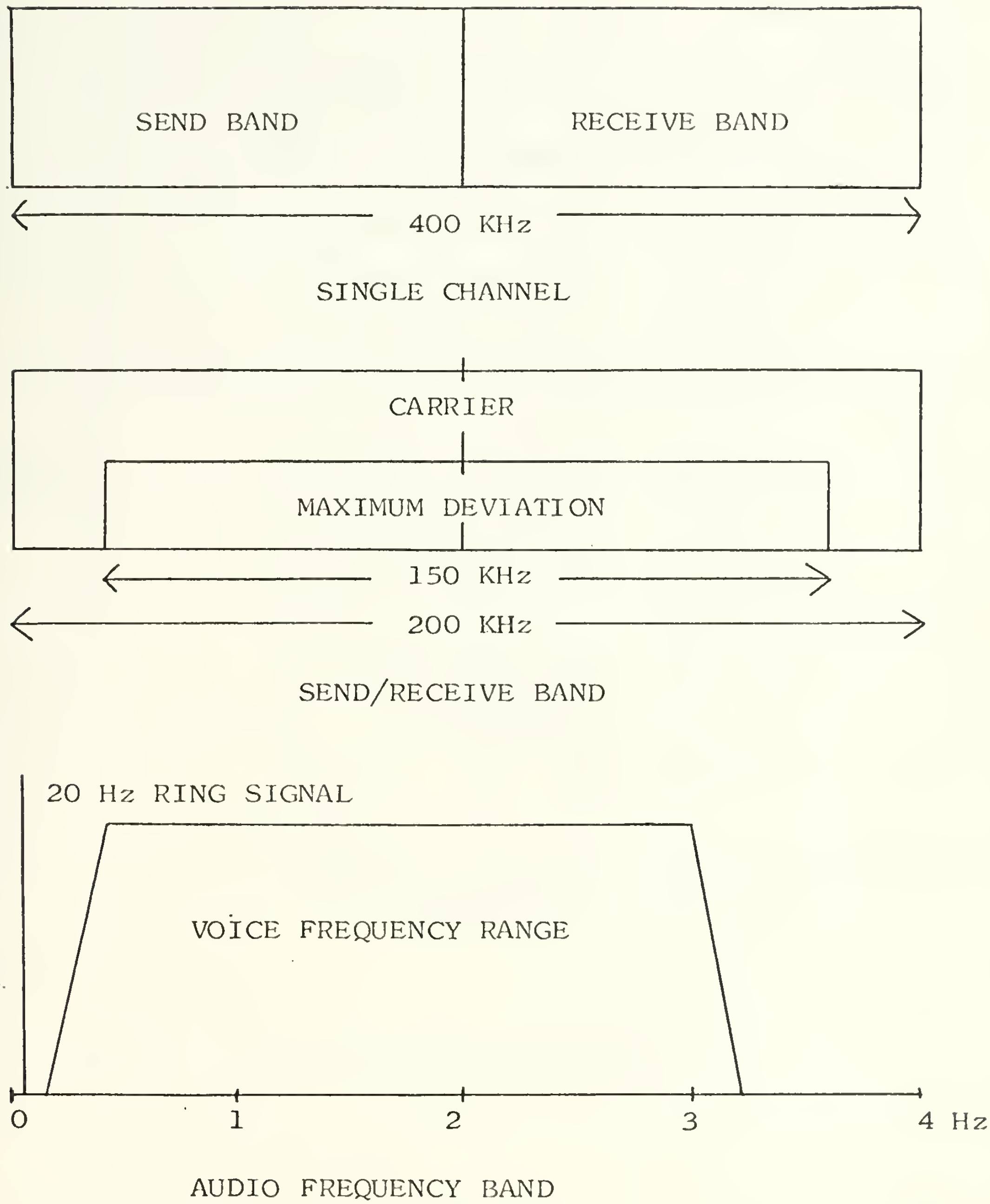

Figure 1. Frequency Allocation

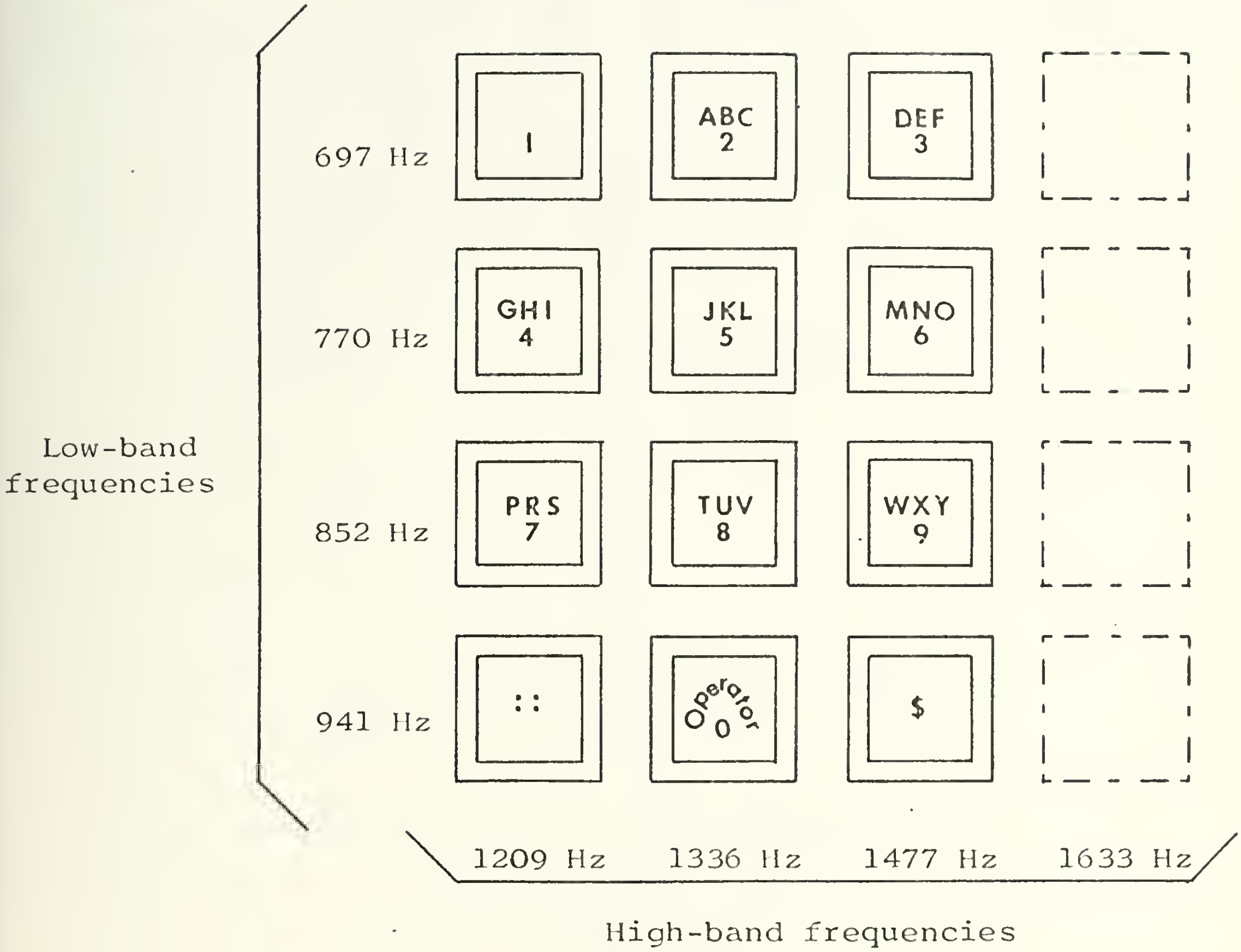

Figure 2. Pushboard Dialing Keyboard

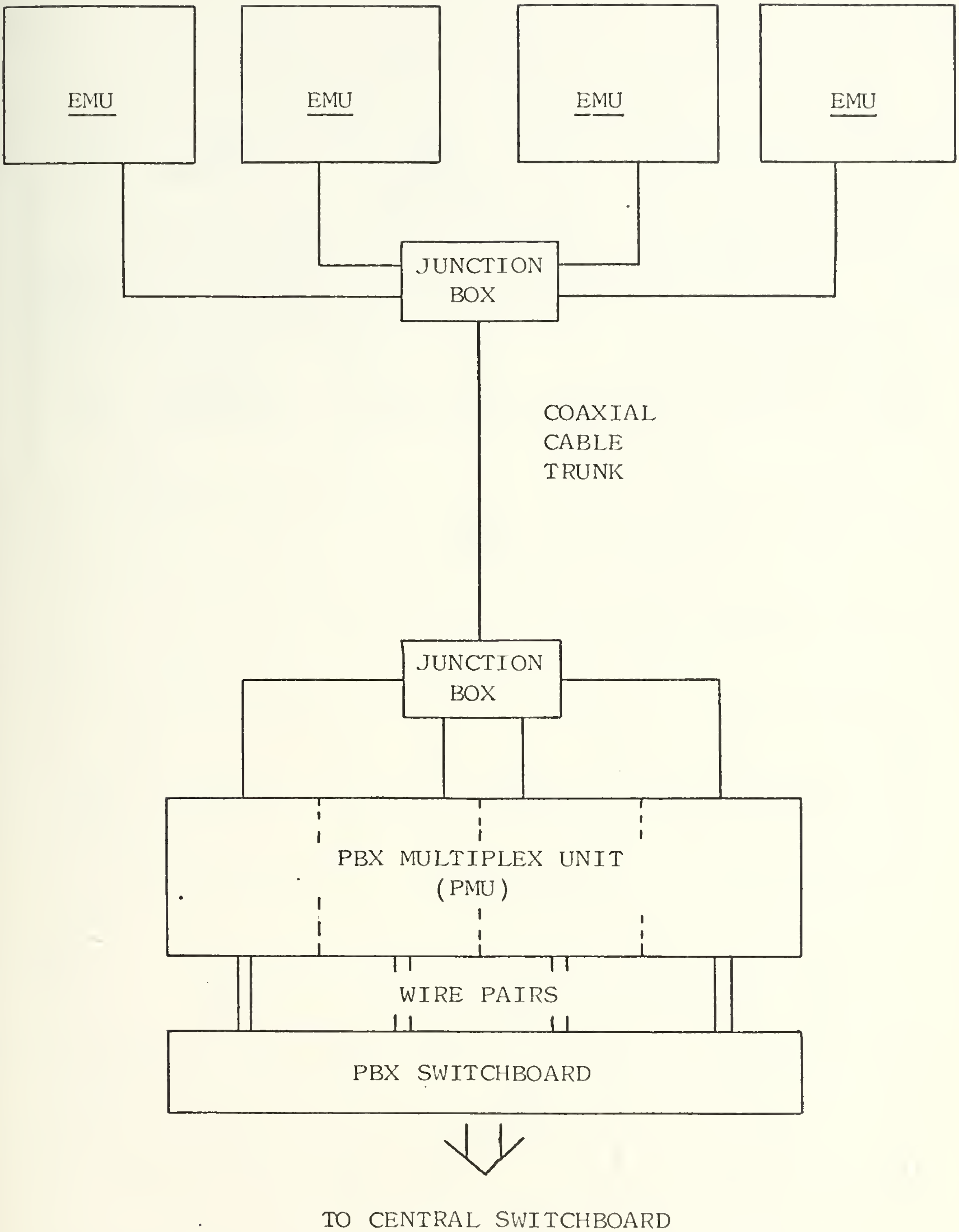

Figure 3. System Block Diagram

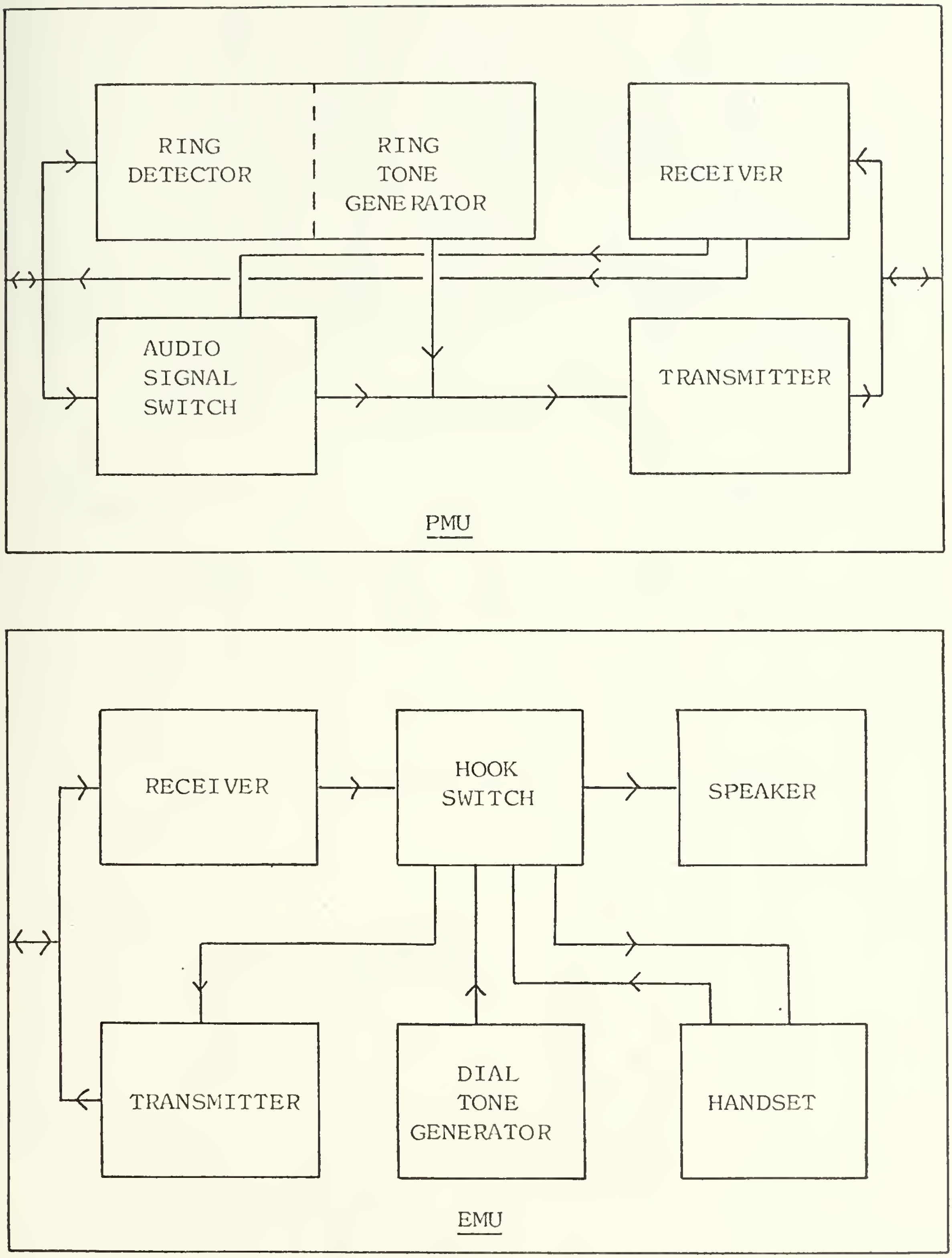

Figure 4. PMU and EMU Block Diagrams

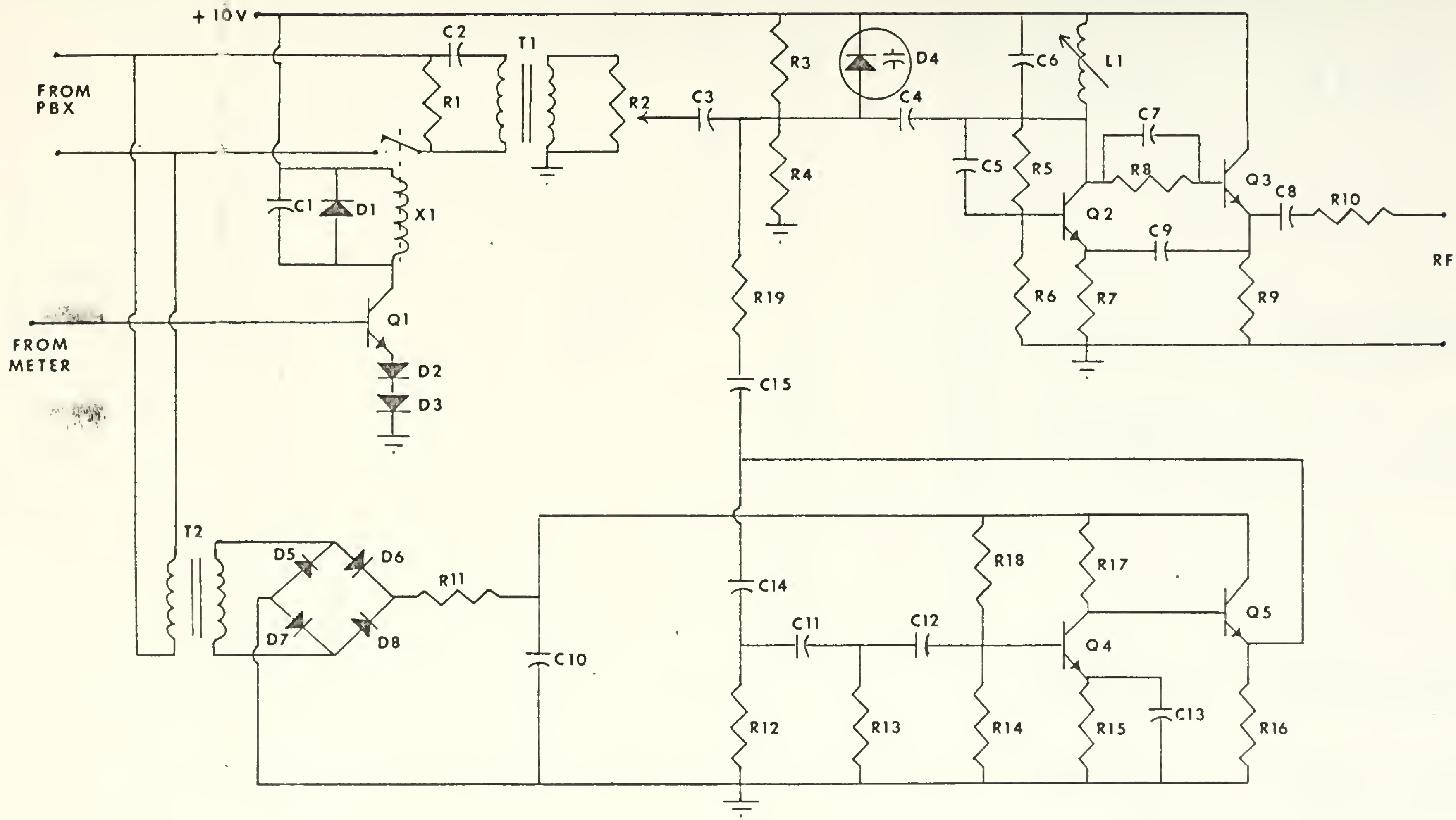

Figure 5. PMU Transmitter Schematic Diagram

R1	680	R7	2.2K	R13	10K
R2	5K pot.	R8	10K	R14	10K
R3	390K	R9	1K	R15	1K
R4	1M	R10	5K	R16	2K
R5	6.2K	R11	100K	R17	10K
R6	1K	R12	10K	R18	100K
				R19	100

C1	.01	C6	.00008 *	C11	.025
C2	.01	C7	.00033	C12	.005
C3	.01	C8	.02	C13	10.00
C4	.00005	C9	.00025	C14	.01
C5	.01	C10	5.0	C15	.01

All capacitors in microfarads.
*Value for carrier frequency of 15-25 MHz

L1 1.1-2.5 uh*

*Value for carrier frequency of 15-25 MHz

T1, T2 Allied 6T10PC

D1, D2, D3	1N276
D4	TO-92A
D5, D6, D7, D8	1N1694

Q1, Q2, Q3, Q4 2N5172

X1 Allied AMP 2007

Figure 6. PMU Transmitter Component Values

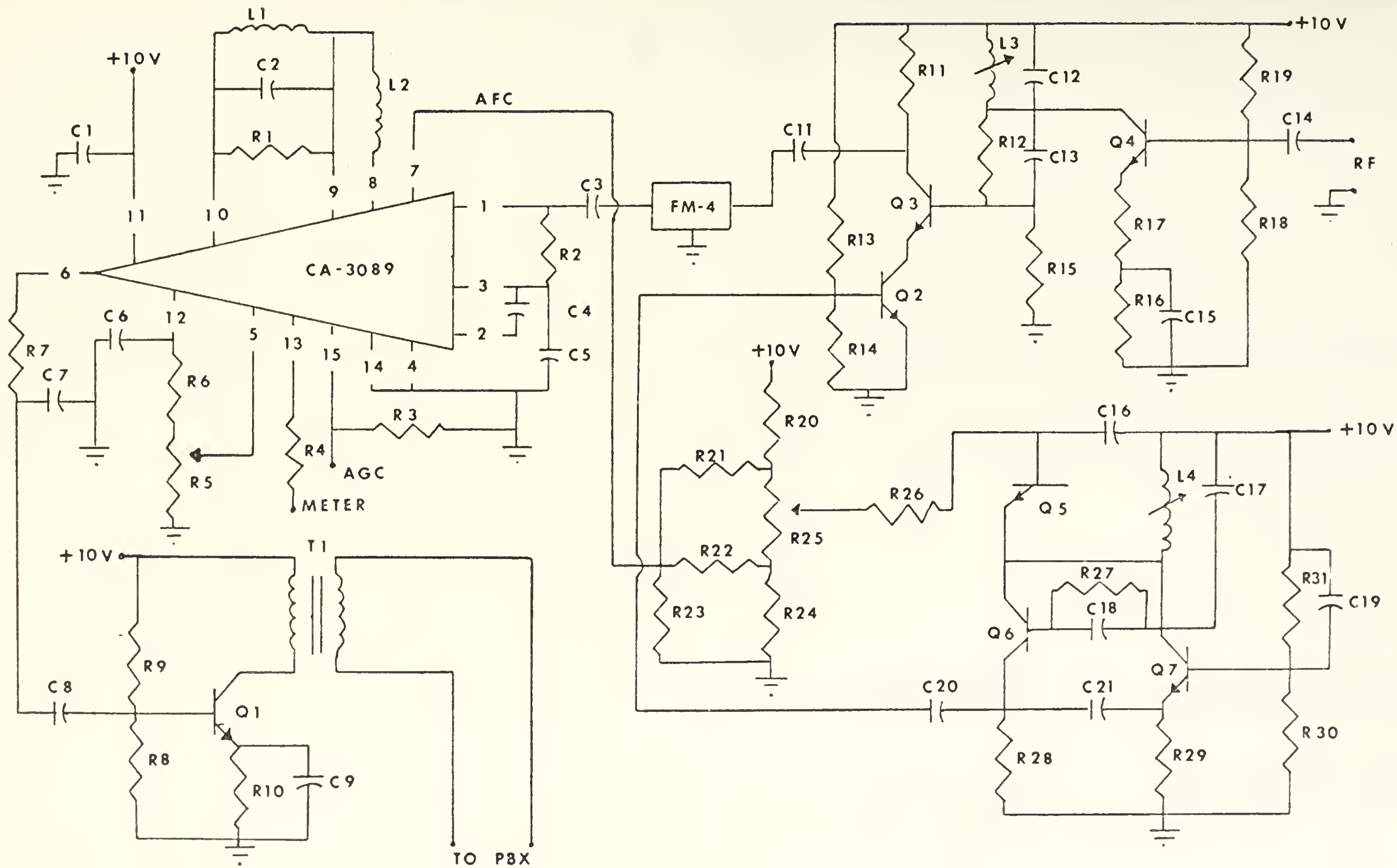

Figure 7. PMU Receiver Schematic Diagram

R1	3.9K	R12	51K	R23	39K
R2	51	R13	100K	R24	39K
R3	10K	R14	10K	R25	10K pot.
R4	33K	R15	10K	R26	2.2K
R5	50K pot.	R16	1K	R27	10K
R6	12K	R17	20	R28	2.2K
R7	2.5K	R18	13K	R29	2.2K
R8	75K	R19	47K	R30	1K
R9	110K	R20	82K	R31	6.2K
R10	100	R21	1K		
R11	1K	R22	1K		

C1	.01	C8	5.0	C15	.01
C2	.0001	C9	.02	C16	.0001
C3	.01	C10	--	C17	.000025*
C4	.01	C11	.02	C18	.00025
C5	.01	C12	.00008*	C19	.01
C6	5.0	C13	.02	C20	.02
C7	.01	C14	.01	C21	.00033

All capacitor values in microfarads.
*Values for carrier frequency of 15-25 MHz.

L1 27 uh   L2 15 uh   L3, L4 1.1-2.5 uh*

*Value for carrier frequency of 15-25 MHz.

T1 Allied 6T10PC

Q1 2N3404
Q2, Q3, Q4, Q5 2N5172

Figure 8. PMU Receiver Component Values

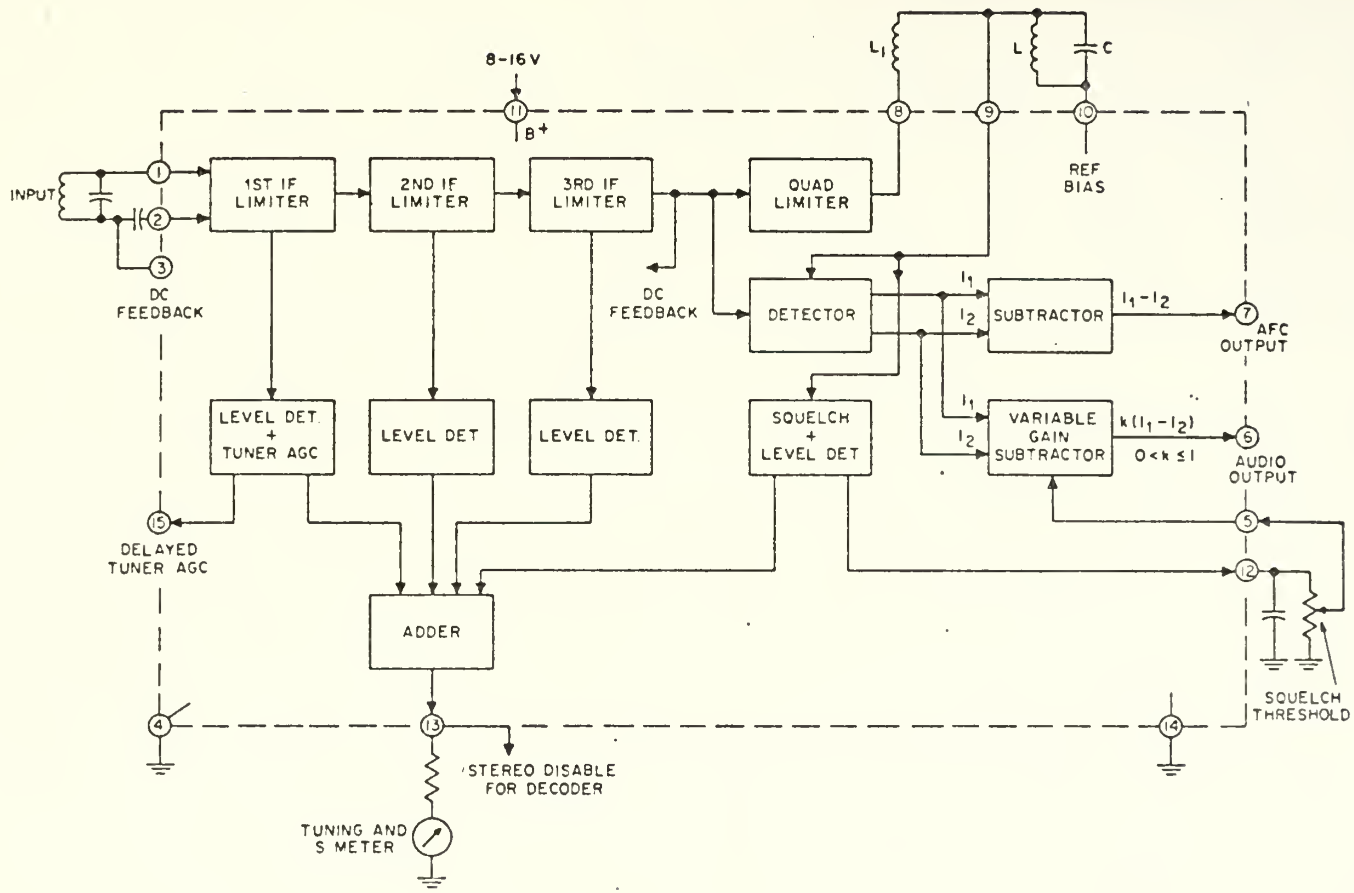

Fig. 9 - Block diagram of the CA3089 FM receiver integrated circuit. The functions enclosed by the dotted line are performed on the chip.

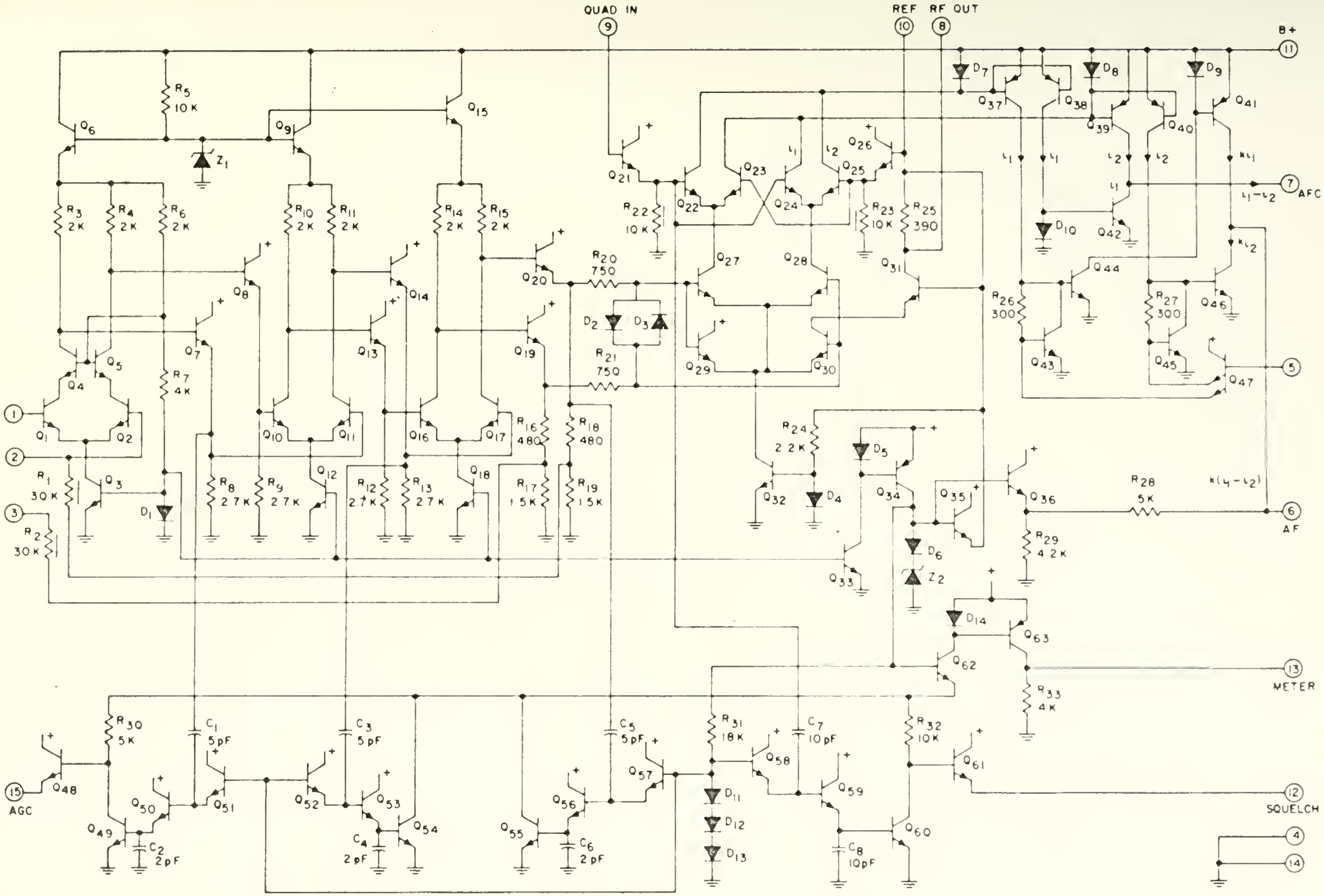

Fig. 10 Functional schematic of the CA3089 multi-function integrated circuit.

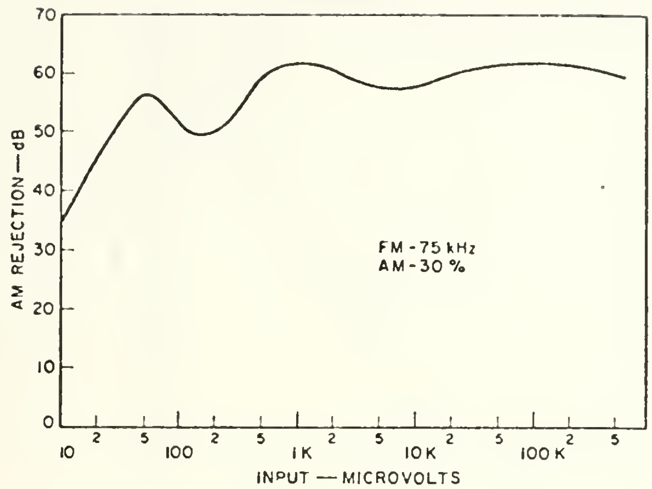

Fig. 11 AM rejection vs i-f input level to the chip.

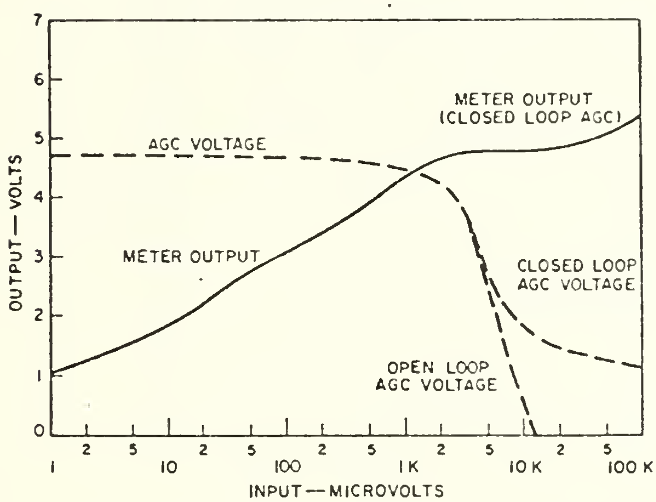

Fig. 12 Typical AGC (pin 15) and meter output (pin 13) vs tuner input signal.

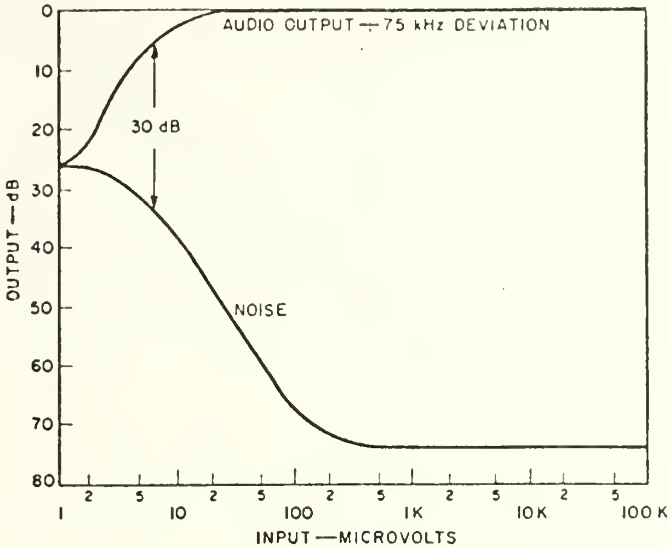

Fig. 13- S+N and N vs input signal to the chip at 10.7MHz. Generator termination is 50 ohms (Fig. 6).

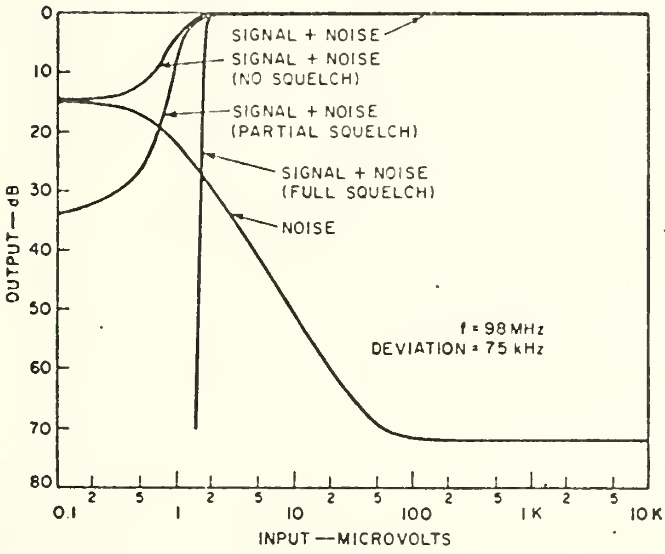

Fig. 14- S+N and N for no squelch, partial squelch, and full squelch, for signal input to a tuner using the CA3089.

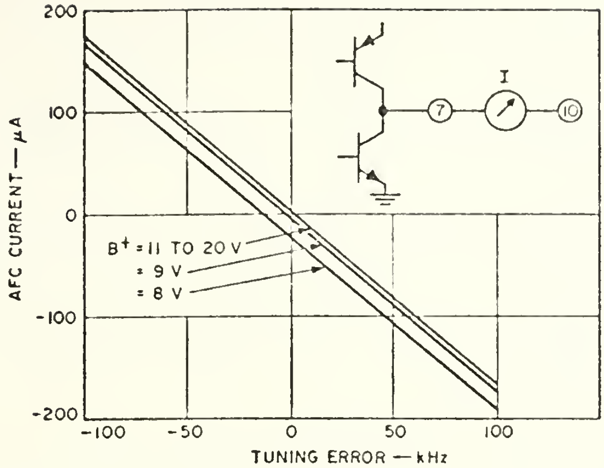

Fig. 15 - AFC output vs tuning error as a function of the supply voltage.

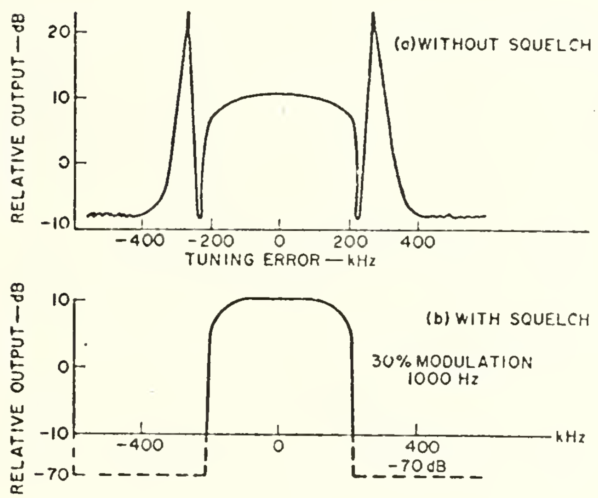

Fig. 16 - Typical tuning characteristic (a) without squelch and (b) with squelch, showing the suppression of the annoying side responses characteristic of limiter-discriminator receivers.

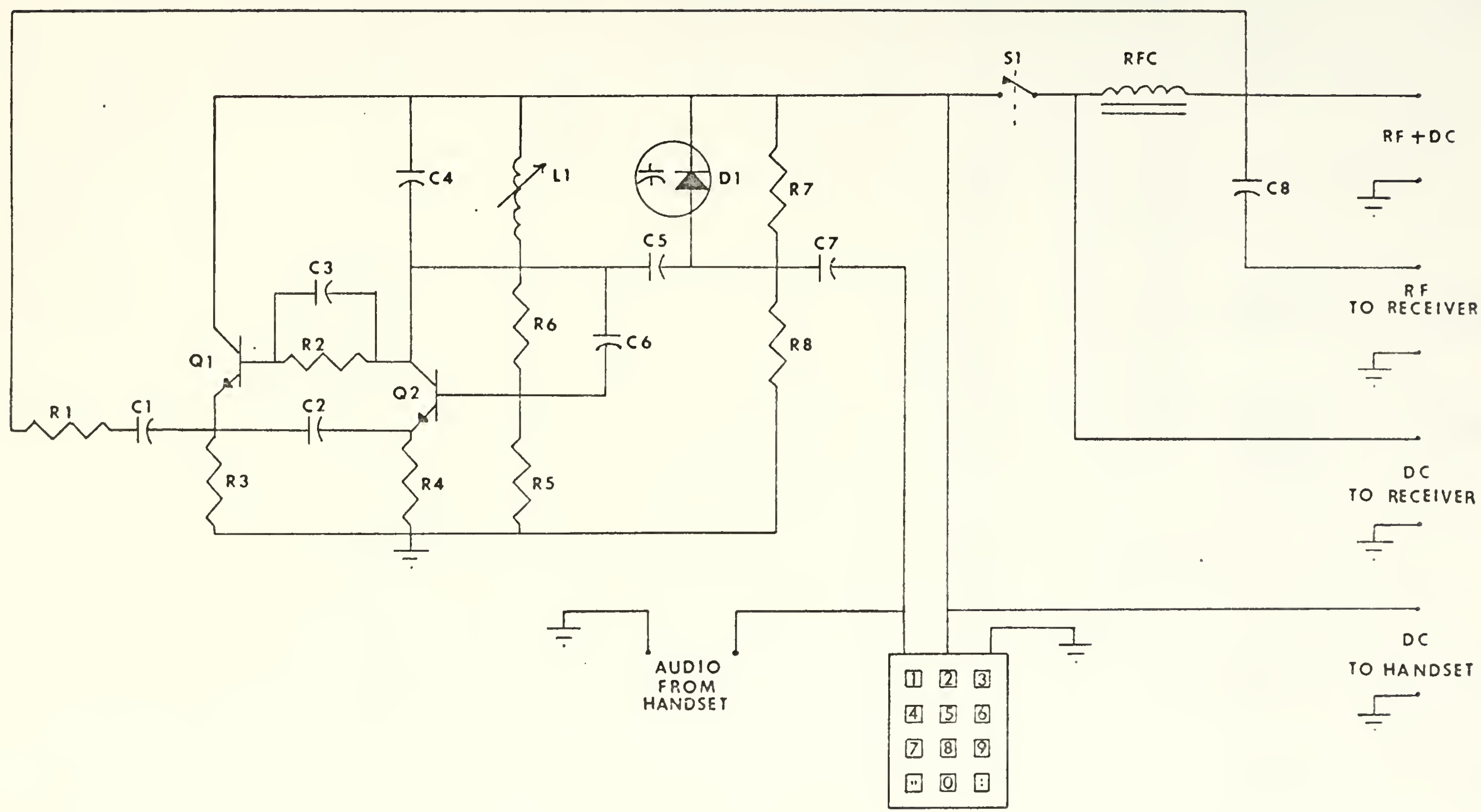

Figure 17. EMU Transmitter Schematic Diagram

R1	5K	R4	2.2K	R7	390K
R2	10K	R5	1K	R8	1M
R3	1K	R6	6.2K		

C1	.02	C4	.00008*	C7	.047
C2	.00025	C5	.00005	C8	.01
C3	.00033	C6	.01		

All capacitors in microfarads
*Value for carrier frequency of 15-25 MHz

L1 1.1-2.5 uh*

*Value for carrier frequency of 15-25 MHz

RFC 2.5 mh

D1 TO-92A

Q1, Q2 2N5172

Figure 18. EMU Transmitter Component Values

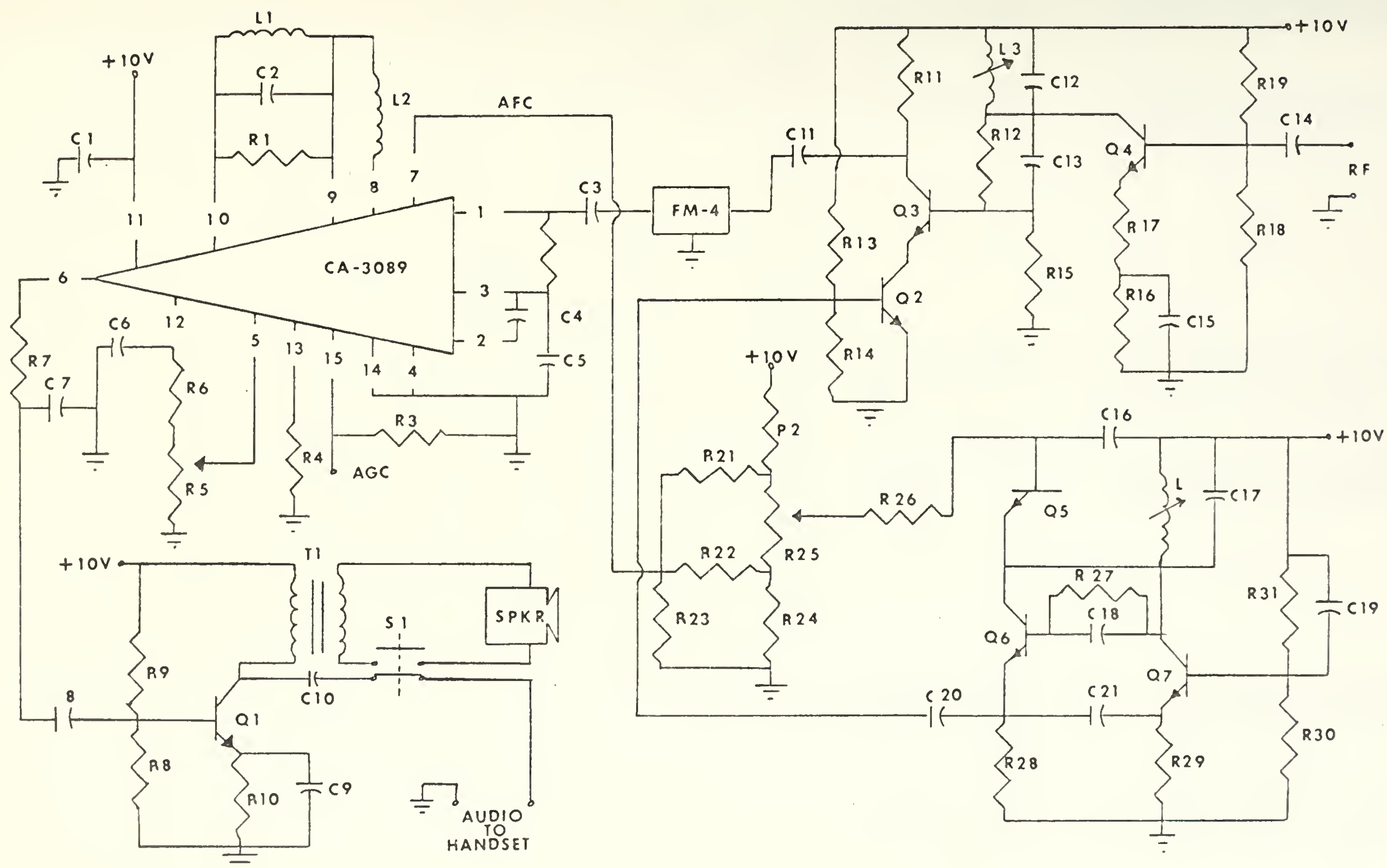

Figure 19. EMU Receiver Schematic Diagram

R1	3.9K	R12	51K	R23	39K
R2	51	R13	100K	R24	39K
R3	10K	R14	10K	R25	10K pot.
R4	33K	R15	10K	R26	2.2K
R5	50K pot.	R16	1K	R27	10K
R6	12K	R17	20	R28	2.2K
R7	2.5K	R18	13K	R29	2.2K
R8	75K	R19	47K	R30	1K
R9	110K	R20	82K	R31	6.2K
R10	100	R21	1K		
R11	1K	R22	1K		

C1	.01	C8	5.0	C15	.01
C2	.0001	C9	.02	C16	.0001
C3	.01	C10	5.0	C17	.000025*
C4	.01	C11	.02	C18	.00025
C5	.01	C12	.00008*	C19	.01
C6	5.0	C13	.02	C20	.02
C7	.01	C14	.01	C21	.00033

All capacitor values in microfarads.
*Values for carrier frequency of 15-25 MHz.

L1	27uh	L2	15 uh	L3, L4	1.1-2.5 uh*

*Value for carrier frequency of 15-25 MHz.

T1 Stancor T11

Q1	2N3404
Q2, Q3, Q4, Q5	2N5172

Figure 20. EMU Receiver Component Values

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BSTRACT

A multichannel frequency division multiplexed FM telephone system is presented. The system is intended for use in organizations where large numbers of telephones are normally installed and is compatible with conventional switchboards. Advantages provided by the system are: reductions in installed wiring, the ability to relocate telephone sets by the subscriber, and compatibility with other coaxial cable systems.

Thesis
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A cable carrier FM telephone system.